Transportation Literature Search

Prepared by
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Wisconsin Department of Transportation Research and Communication Services

Pile Downdrag

Prepared for
Wisconsin Highway Research Program
Geotechnics Technical Oversight Committee

November 22, 2006

Transportation Literature Searches are prepared for WisDOT staff and principal investigators to heighten awareness of completed research in areas of current interest. The citations below are representative, rather than exhaustive, of available English-language studies on the topic. Primary online resources for the literature searches are the Transportation Libraries Catalog (TLCat), the Transportation Research Information Service (TRIS Online), National Transportation Library (NTL), Research in Progress (RiP) Compendex/Engineering Village, Web of Science, and other academic and scientific databases when requests merit. Online copies of publications are noted when available. Hard copies of cited literature may be obtained through the WisDOT Library; contact John Cherney at john.cherney@dot.state.wi.us or 608-266-0724.

SUMMARY

The Geotechnics Technical Oversight Committee of the Wisconsin Highway Research Program requested a Transportation Literature Search on the topic of pile downdrag, or negative skin friction. Specific interest was expressed in how downdrag develops, how its magnitude is computed, and what is done to resist its effects.

We found a total of 23 citations in the above databases dating back through 2002. Fully 18 of these citations originate in academic and professional peer-reviewed journals. Four articles are drawn from conference proceedings, and one from a trade newsletter. When considered by year, 2004 led the way with nine published reports; there were six citations from 2006, three from 2005 and 2002, and two from 2003. No citations predated 2002.

We arrange these citations according to subtopic. Although there is crossover in the categories below, we group the citations according to downdrag **Characteristics** (nine citations), **Measurement and Modeling** of downdrag (nine citations), and treating downdrag via **Mitigation and Design** (five citations).

KEYWORDS

downdrag, pile, negative, skin, friction

CITATIONS – Characteristics

Title: Discussion of "Development of downdrag on piles and pile groups in consolidating soil" by C.J. Lee and Charles W.W. Ng
Author(s): Frank M. Geotechnical (sic)
Date: April 2006
Doc ID/URL: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132 (4), April 1 2006: 547.
Description: 1 p.
Contents: Not available.

Title: The influence of soil slip on negative skin friction in pile groups connected to a cap
Author(s): C.J. Lee, J. H. Lee, S. Jeong
Date: 2006
Doc ID/URL: *Geotechnique*, Vol. 56 (1), February 2006: 53-56.
Description: 4 pp.
Contents: Not available.

Title: Performance of pile-supported bridge approach slabs
Author(s): Reda M. Bakeer, Mark A. Shutt, Jianquiang Zhong, Sankar C. Das, Mark Morvant

Date: March/April 2005
Doc ID/URL: *Journal of Bridge Engineering*, Vol. 10 (2), March/April 2005: 228-237.
Description: 10 pp.
Contents: A large number of pile-supported bridge approach slabs in southeastern Louisiana were examined to identify the factors that affect their long-term performance. Design drawings and subsoil conditions at these sites as well as their traffic and maintenance records were compiled, and seven representative test sites were selected for thorough field investigation that included inspection of the approach slabs, bridge decks, bridge abutments, and roadway pavement. Field evaluation included walking profiler, falling-weight deflectometer (FWD), laser profiler, geodetic survey, soil borings, cone penetrometer, and nondestructive testing. Measurements made with the walking profiler agreed well with the geodetic survey. The FWD and nondestructive testing were effectively used to detect voids under the approach slab. Results of the study indicated that the current empirical methodology used by the Louisiana Department of Transportation and Development for design of pile-supported approach slabs yields inconsistent field performance. It was concluded that this inconsistent performance is primarily due to the differences in roadway embankment design and construction and in subsoil conditions, which in turn affect the negative skin friction (downdrag) loads imparted on the piles. Impact of other variables such as ramp type, speed limit, traffic volume, and so on was found to be insignificant. Results of the field study were used to develop a new rating system for approach slabs (IRIS) based on International Roughness Index (IRI) measurements obtained with the laser profiler.

Title: Behavior of pile subject to negative skin friction and axial load
Author(s): C.F. Leung, B.K. Liao, Y.K. Chow, R.F. Shen, Y.C. Kog
Date: December 2004
Doc ID/URL: *Soils and Foundations*, Vol. 44 (6), December 2004: 17-26.
Description: 10 pp.
Contents: Centrifuge model tests have been conducted to investigate the effect of negative skin friction on piles installed through soft clay and founded in underlying dense sand. The first test series involved the study of fundamental mechanism of piles subject to negative skin friction only. In these tests, negative skin friction was induced by self-weight consolidation of clay followed by in-flight sand surcharge placement on the clay. The second test series examined the behavior of piles subject to simultaneous negative skin friction and axial load. The effects of axial load on the load-transfer characteristics along a pile experiencing locked-in negative skin friction induced by consolidating clay are investigated in detail in this paper. The effects of pile tip condition (end-bearing or socket pile), pile socket length and magnitude of applied load on the pile are also studied.

Title: Development of downdrag on piles and pile groups in consolidating soil
Author(s): C.J.. Lee, Charles W.W. Ng
Date: September 2004
Doc ID/URL: *Journal of Geoenvironmental Engineering*, Vol. 130 (9), September 2004: 905-914.
Description: 10 pp.
Contents: Development of pile settlement (downdrag) of piles constructed in consolidating soil may lead to serious pile foundation design problems. The investigation of downdrag has attracted far less attention than the study of dragload,over the years. In this paper, several series of two-dimensional axisymmetric and three-dimensional numerical parametric analyses were conducted to study the behavior of single piles and piles in 3 × 3 and 5 × 5 pile groups in consolidating soil. Both elastic no-slip and elasto-plastic slip at the pile-soil interface were considered. For a single pile, the downdrag computed from the no-slip elastic analysis and from the analytical elastic solution was about 8-14 times larger than that computed from the elasto-plastic slip analysis. The softer the consolidating clay, the greater the difference between the no-slip elastic and the elasto-plastic slip analyses. For the 5 × 5 pile group at 2.5 diameter spacing, the maximum downdrag of the center, inner, and corner piles was, respectively, 63, 68, and 79% of the maximum downdrag of the single pile. The reduction of downdrag inside the pile group is attributed to the shielding effects on the inner piles by the outer piles. The relative reduction in downdrag (W_r) in the 5 × 5 pile group increases with an increase in the relative bearing stiffness ratio (E_b/E_c,), depending on the pile location in the group. Compared with the relative reduction in dragload (P_r), W_r at the corner pile is less affected by the group interaction for a given surcharge load. This suggests that the use of sacrificing piles outside the pile group will be more effective on P_r than on W_r. Based on the three cases studied, the larger the number of piles in a group, the greater the shielding effects on W_r. Relatively speaking, W_r is more sensitive to the total number of piles than to the pile spacing within a pile group. © ASCE.

Title: Slip effect at the pile-soil interface on dragload
Author(s): Sangseom Jeong, Jinhyung Lee, Cheol Ju Lee
Date: March 2004

Doc ID/URL: *Computers and Geotechnics*, Vol. 31 (2), March 2004: 115-126.
Description: 12 pp.
Contents: Negative skin friction is perhaps one of the most common problems in the design of pile foundations in soft soils. The development of dragload on single piles and piles in groups in consolidating ground was investigated from 2D and 3D elasto-plastic numerical analyses. Conventional no-slip continuum analysis and slip analysis were conducted for comparison. The parametric analyses showed that dragload for single piles and their reductions in pile groups were substantially over-estimated by the continuum analyses. Axial loading of about 125-325% of the maximum dragload was required to eliminate dragload, depending on the stiffness of the bearing layer. Dragload development heavily depended on the interface friction coefficient, surface loading, and axial load, governing soil slip behavior at the pile-soil interface. The application of axial loads on piles in groups resulted in reductions in group effects. An example analysis and two previous experimental observations of dragload and group effects were back-analyzed. The slip analysis estimated reasonable dragload and group effect, whereas unrealistic computations were obtained from the no-slip continuum analysis. © 2004 Elsevier Ltd. All rights reserved.

Title: Negative skin friction on piles due to lowering of ground water table
Author(s): C.J. Lee, C.R. Chen
Date: April 2003
Doc ID/URL: *Geotechnical Engineering*, Vol. 34 (1), April 2003: 13-24.
Description: 12 pp.
Contents: Negative skin friction forces mobilized on piles due to settlement induced by self-weight consolidation of soil and lowering of the water table were studied in the paper. Two instrumented model piles were used to measure the axial forces on the piles in centrifuge model tests conducted at an acceleration of 50 g. The settlement of the pile tip caused the neutral plane to move upward thereby reducing the negative skin friction forces. The negative skin friction force decreased with decreasing spacing to diameter ratio of piles and with increasing number of neighboring piles. However, the negative skin friction force on a pile in a pile group is almost the same as that on an isolated pile if its spacing from other piles is larger than six times the pile diameter. In addition, inner piles within a group experience lower negative skin friction forces than outer piles. The concept of an average effective pile number was proposed for estimating the average reduction factor of the negative skin friction force for grouped piles. The analytical results were in reasonable agreement with those measured in the centrifuge model tests. The present results indicate that groundwater recharge in a subsidence region will rapidly and effectively mitigate the pile axial forces induced by negative skin friction.

Title: Bearing capacity and settlement of pile foundations
Author(s): George Geoffrey Meyerhof
Date: 2002
Doc ID/URL: *Geotechnical Special Publication No. 118 (II),* 2002: 1684-1715.
Description: 32 pp.
Contents: The bearing capacity and settlement of pile foundations was investigated. The methods of soil exploration used to ascertain the character of natural deposits were also discussed. The negative skin friction on a point-bearing pile group passing through consolidating soft clay or silt was also estimated.

Title: Case histories of problems with timber piles
Author(s): James S. Graham, Lawrence F. Johnsen
Date: 2002
Doc ID/URL: *Geotechnical Special Publication n 116 (I),* 2002: 587-603.
Description: 7 pp.
Contents: The object of this publication is to alert readers about the problems and unknowns associated with timber piling. Included are 21 case histories of problems with treated wood piling dealing with installation, usage, marine effects, and environmental impacts. Eight of the case histories concern the most serious problem, the breakage of timber piling during construction (see Figure 1). Usage problems include downdrag, settlement, degradation of wood, and potential fire hazards. Problems in salt-waters include marine borer attack, Chromated Copper Arsenate (CCA) sheathing that fails in about 10-years, breaking from impact forces, and excessive spiral grain. Environmental problems involve preservatives leaching into the water. The three major building codes, BOCA, SBC, and UBC, publish creosote treated timber piling compressive design stresses of 8.6 MPa (1250 psi) for Douglas fir and 8.3 MPa (1200 psi) for southern pine. Compression parallel to grain tests on southern pine timber piling give average values as low as 15.5 MPa (1820 psi). The result is an inadequate safety factor of about 1.5. To be safe, engineers should consider designing creosote treated piling with 6.2 MPa (900) psi for Douglas fir and 5.5 MPa (800 psi) for southern pine.

CITATIONS – Measurement and Modeling

Title: A procedure for theoretical estimation of dewatering-induced pile settlement
Author(s): Shuhua Chen, Yanyong Xiang
Date: June/July 2006
Doc ID/URL: *Computers and Geotechnics*, Vol. 33 (4-5), June/July 2006: 278-282.
Description: 5 pp.
Contents: Dewatering in geotechnical excavations may cause soil consolidation and settlement, which would exert negative skin friction on nearby piles and cause additional pile settlements. Incorporating four steps that include a pumping model, a simplified consolidation evaluation, a pile-soil interaction model and a semi-theoretical pile settlement prediction, this paper presents a procedure to estimate the drawdown, the soil consolidation settlement, the negative friction on the pile shaft and the additional pile settlement, induced by dewatering in phreatic zones. Numerical calculations for a simplified situation of dewatering operation illustrate the proposed procedure in estimating the mechanical effects of dewatering on nearby piles. © 2006 Elsevier Ltd. All rights reserved.

Title: Results from long-term measurement in piles of drag load and downdrag
Author(s): Bengt H. Fellenius
Date: April 2006
Doc ID/URL: *Canadian Geotechnical Journal*, Vol. 43 (4), April 2006: 409-430.
Description: 22 pp.
Contents: Several full-scale, long-term tests on instrumented piles performed since the 1960s and through the 1990s are presented. The results of the tests show that a large drag load will develop in piles installed in soft and loose soils. The test cases are from Norway, Sweden, Japan, Canada, Australia, United States, and Singapore and involve driven steel piles and precast concrete piles. The test results show that the transfer of load from the soil to the pile through negative skin friction, and from the pile back to the soil through positive shaft resistance, is governed by effective stress and that already a very small movement will result in mobilization of ultimate values of shaft shear. The pile toe resistance, on the other hand, is determined by downdrag of the pile and the resulting pile toe penetration. Reconsolidation after the pile installation with associated dissipation of pore pressures will result in significant drag load. An equilibrium of force in the pile will develop, where the sustained loads on the pile head and the drag load are equal to the positive shaft resistance plus the pile toe resistance. The location of the force equilibrium, the neutral plane, is also where the pile and the soil move equally. The drag load is of importance mostly for very long piles (longer than 100 pile diameters) for which the pile structural strength could be exceeded. Downdrag, i.e., settlement of the piled foundation, is a very important issue, however, particularly for low-capacity short piles. Soil settlement at the neutral plane will result in a downdrag of the pile. The magnitude of the downdrag will determine the magnitude of the pile toe penetration into the soil, which will determine the pile toe resistance and affect the location of the neutral plane. Nature's iteration of force and soil settlement will decide the final location of the neutral plane. © 2006 NRC Canada.

Title: Evaluation of negative skin friction effects in pile foundations using 3D nonlinear analysis
Author(s): Emilios M. Comodromos, Spyridoula V. Bareka
Date: April 2005
Doc ID/URL: *Computers and Geotechnics*, Vol. 32 (3), April 2005: 210-221.
Description: 12 pp.
Contents: The aim of this paper is to evaluate the influence of negative skin friction in pile foundations. Three dimensional nonlinear analyses for a single pile and pile groups were carried out for a specific case and some case studies as well. Contrary to simplified conventional analysis in which the predictions are usually overestimated and could be considered as an upper limit, it was found that the dragload of a pile in a group depends on the surface load, the pile configuration, the pile position in a group, the ultimate skin friction and the interface stiffness. It has been demonstrated that for fixed-head friction pile groups the dragload group effect is significantly greater than in the case of free-head end-bearing pile groups. Moreover, predictions for internal piles have shown considerably smaller dragloads for fixed-head piles, which is in accordance with experimental findings. It has also been demonstrated that when the construction of an embankment precedes the application of the foundation working load, the effect of negative skin friction is considerably smaller than in the reverse case. © 2005 Elsevier Ltd. All rights reserved.

Title: Static loading test on a 45 m long pipe pile in Sandpoint, Idaho
Author(s): Bengt H. Fellenius, Dean E. Harris, Donald G. Anderson
Date: August 2004
Doc ID/URL: *Canadian Geotechnical Journal*, Vol. 41 (4), August 2004: 613-628.
Description: 16 pp.

Contents: Design of piled foundations for bridge structures for the realignment of US95 in Sandpoint, Idaho, required a predesign static loading test on an instrumented, 406 mm diameter, closed-toe pipe pile driven to 45 m depth in soft, compressible soil. The soil conditions at the site consist of a 9 m thick sand layer on normally consolidated, compressible, postglacial alluvial deposits to depths estimated to exceed 200 m. Field explorations included soil borings and CPTu soundings advanced to a depth of 80 m. The clay at the site is brittle and strain-softening, requiring special attention and consideration in geotechnical design of structures in the area. Effective stress parameters back-calculated from the static loading test performed 48 days after driving correspond to beta coefficients of about 0.8 in the surficial 9 m thick sand layer and 0.15 at the upper boundary of the clay layer below, reducing to 0.07 in the clay layer at the pile toe, and a pile toe bearing coefficient of 6. The beta coefficients are low, which is probably due to pore pressures developing during the small shear movements during the test before the ultimate resistance of the clay was reached. The analyses of the results of the static loading test have included correction for residual load caused by fully mobilized negative skin friction down to 10 m depth and fully mobilized positive shaft resistance below 30 m depth, with approximately no transfer of load between the pile and the clay from 10 m depth through to 30 m depth. © 2004 NRC Canada.

Title: Full-scale load tests on instrumented micropiles
Author(s): Gianpiero Russo
Date: July 2004
Doc ID/URL: *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, Vol. 157 (3), July 2004: 127-135.
Description: 9 pp.
Contents: In September 2001, following an exceptional rainfall event with an estimated return time of about 500 years, a number of ancient buildings located in a restricted area in the historical centre of Napoli underwent significant settlement and heavy structural damage. Structural collapse on saturation of the pyroclastic soils and loss of bearing capacity by submersion are believed to be the origin of the observed phenomena. After the settlements came to a standstill, a subsoil investigation was carried out and a remedial solution was designed, based on a massive underpinning of the damaged buildings by micropiles. The size of the project and the well-known dependence of the behaviour of micropiles on technological details suggested that some preliminary load tests on piles should be undertaken. The results of two load tests on instrumented piles installed with different procedures are reported and discussed. A new technique to install embedded vibrating wire gauges was tested, and was revealed to be successful. The experimental findings are in good agreement with the Bustamante and Doix method. Also, the simplified approach proposed by Randolph and Wroth to evaluate the stiffness of the soil layer was checked, providing good results. The experimental finding about the mobilisation of some negative skin friction along the pile shaft, probably due to the large grouted volumes, is confirmed by several finite element analyses.

Title: Model pile pull-out tests using polyethylene sheets to reduce downdrag on cast in situ piles
Author(s): S.H. Chow, K.S. Wong
Date: May 2004
Doc ID/URL: *Geotechnical Testing Journal*, Vol. 27 (3), May 2004: 230-238.
Description: 9 pp.
Contents: Low-density polyethylene sheets (LDPE) were used in this study to investigate its effectiveness in reducing downdrag on cast in situ piles. Eight model pile pull-out tests were conducted using three reinforced concrete circular model piles with different surface conditions (smooth, smooth with necking and bulging, and rough) in combination with three different LDPE sheet arrangements (one-sheet, two-sheet, and three-sheet). The pile was embedded partially in Ottawa sand with a surcharge of 19.3 kPa on sand surface. The test results showed that an arrangement with 3 pieces of 0.25-mm thick LDPE sheet was most effective in reducing side friction up to an average of 89%. It was also found that the effectiveness of LDPE sheets is independent of the concrete surface roughness. However, the presence of necking and bulging was found to increase the side resistance up to 40% for the plain pile without LDPE sheets.

Title: Dynamic measurement and analysis of pile driving through thick soft clay (In *Current Practices and Future Trends in Deep Foundations*)
Author(s): C.E. Ho, C.H. Lim
Date: 2004
Doc ID/URL: *ASCE Geotechnical Special Publication 125*, 2004: 329-347.
Description: 19 pp.
Contents: Dynamic measurements using a Pile Driving Analyzer (PDA) were performed on a 205mm x 205 square reinforced concrete pile during a pile-driving study through thick soft marine clay into dense old alluvium. A two-stage driving program was introduced to obtain the downdrag load likely to be experienced on the site required for

foundation design. Measured driving stresses were comparable with the conventional method proposed by Broms (1981) for calculating pile head stresses. CAPWAP analyses were conducted on data obtained at the start of redrive at 19m, end of redrive at 27.45m and restrike carried out 2 hours later. Pile capacities determined from Case method, CAPWAP and the simplified pile driving formula proposed by Broms and Lim (1988) were compared and discussed. Interpretation of soil behavior was made based on the measured force and velocity traces, as well as soil resistance distribution obtained from CAPWAP. The derivation of working load for the pile and its probable performance under downdrag load in the long term was obtained by constructing the ultimate load transfer envelop and the pile top load-displacement response from those given by CAPWAP.

Title: Full scale load tests on instrumented micropiles: Technology and behaviour
Author(s): G. Russo, C. Viggiani
Date: 2003
Doc ID/URL: *BGA International Conference on Foundations, Innovations, Observations, Design and Practice 2003*: 777-786.
Description: 10 pp.
Contents: A preliminary load tests (sic) on piles was carried out on massive underpining (sic) of the damaged buildings by micropiles. The pile behaviour in terms of both bearing capacity and settlement was strongly dependent on the installation procedure. The measurement of load transfer along the pile shaft allowed a reliable estimate of the ultimate skin friction. The finite element analysis showed that the use of large grouted volumes in the lower part of a pile mobilised some negative skin friction.

Title: Numerical modeling of group effects on the distribution of dragloads in pile foundations
Author(s): C.J. Lee, M.D. Bolton, A. Al-Tabbaa
Date: June 2002
Doc ID/URL: *Geotechnique*, Vol. 52 (5), June 2002: 325-335.
Description: 11 pp.
Contents: Negative skin friction on pile foundations, predicted from the results of numerical analyses, is presented. Soil slip at the pile-soil interface has been found to be the most important factor in governing pile behaviour in consolidating ground. Reduction in dragload is predicted for piles in a group owing to interaction between soil and pile. It has been demonstrated that the group effect depends not only on the configuration of the pile group, but also on soil along the pile-soil interface, governed mainly by the interface friction coefficient and the soil settlement. Various factors should be included in an evaluation of the group effect, including the pile spacing, the number of piles in a group, the relative location of piles in a group, the pile type, the pile installation method, the surface loading and the stiffness of the soil. Existing design approaches result in overprediction of dragload for a single pile and of group effect for a pile group. Back-analysed dragloads and group effects considering soil slip are compared with a number of case histories.

CITATIONS – Mitigation and Design

Title: Pile foundation design – Clarification of a confusion
Author(s): Bengt H. Fellenius
Date: June 2006
Doc ID/URL: *Geotechnical News*, Vol. 24 (2), June 2006: 43-45.
Description: 3 pp.
Contents: A frequent confusion and lack of understanding exists with regard to the design of piles subjected to drag loads. Some will lump the drag load in with the dead and live loads when assessing pile bearing capacity. Also common is to disregard the root of the problem: settlement of the piled foundation. It must be realized that: dead and live loads applies to bearing capacity, dead load and drag load applies to structural strength, and downdrag is settlement. A few weeks ago, I was once again asked if the allowable load for a pile should be reduced when considering drag load. Shortly thereafter, when I took a look at the discussions at www.Geoforum.com, I noticed a very similar question. Perhaps I should not be that taken aback by the lack of knowledge displayed by the questions. The persons asking may not have been taught better. The following is a quote from a textbook published in 2001 and assigned to 4th Year Civil Engineering students at several North American Universities: Piles located in settling soil layers are subjected to negative skin friction called downdrag. The settlement of the soil layer causes the fric tion forces to act in the same direction as the loading on the pile. Rather than providing resistance, the negative skin friction imposes additional loads on the pile. The net effect is that the pile load capacity is reduced and pile settlement increases. The allowable load capacity is given as: $Q_{allow} = Q_{ult}/F_s - Q_{neg}$ where Q_{allow} = Allowable load capacity Q_{ult} = Load capacity F_S = Factor of safety Q_{neg} = Downdrag First, "negative skin friction" is not "downdrag" but defines a downward directed shear force along the pile, while downdrag is the term for settlement of

a pile (caused by the settling soil 'dragging a pile along'). Second, the term "load capacity" means different things to different people and "allowable load capacity" is an abominable concoction of words. Third, and very important, the phrasing in the quoted paragraph confuses cause and effect. Drag load is not downdrag, and it does not cause settlement, but is caused by settlement of the surrounding soil and is mobilized when the pile resists this settlement. The worst boo-boo, however, lies in the quoted formula, which does not recognize that the factor of safety and the drag load are interconnected, i.e., changing the factor of safety changes the drag load. As this may not be immediately clear to all, the following example will try to clarify the interaction between the pile, the factor of safety, and the drag load.

Title: Drag force on single piles in clay subjected to surcharge loading
Author(s): Adel M. Hanna, Ali Sharif
Date: March 2006
Doc ID/URL: *International Journal of Geomechanics*, Vol. 6 (2), March 1, 2006: 89-96.
Description: 8 pp.
Contents: Piles driven into clay are often subjected to indirect loading as a result of the surcharge applied on the surrounding area. During the drained period, both the piles and the soil undergo downward movements caused by the axial and the surcharge loading, respectively. Depending on the relative movement of the pile-soil system, positive and negative skin friction develop on the pile's shaft. Negative skin friction is the drag force that may be large enough to reduce the pile capacity and/or to overstress the pile's material causing fractures or perhaps structural failure of the pile, and/or possibly pulling out the pile from the cap. A numerical model that uses the finite element technique combined with the soil responses according to Mohr-Coulomb criteria was developed for case simulation. The computer program CRISP (developed by Cambridge University) was used in this study. The numerical model was first tested against the results predicted by the bearing capacity theories for pile foundations in clay subjected to axial loading. Upon achieving satisfactory results, the numerical model was then used to generate data for piles subjected to surcharge loading. The predicted values were compared well with the field data and the empirical formulae available in the literature. Based on the results of the present investigation, design charts and procedures are presented to predict the location of the neutral plane and to estimate the drag force acting on the pile's shaft for a given pile-soil-loading conditions. In the case of excessive drag force, coating the pile's shaft with a thin layer of bitumen is advisable to eliminate or minimize the drag force. The design procedure presented herein would provide the means to establish the need and the extent of the pile coating. Furthermore, it demonstrates the role of the factor of safety on both pile capacity and the depth of the neutral plane. © 2006 ASCE.

Title: Expanding the use of integral abutments in Iowa
Author(s): Kenneth F. Dunker, Ahmad Abu-Hawash
Date: 2005
Doc ID/URL: *Proceedings of the 2005 Mid-Continent Transportation Research Symposium*, 2005. http://www.ctre.iastate.edu/pubs/midcon2005/DunkerAbutments.pdf.
Description: 13 pp.
Contents: In the mid-1960s Iowa began experimenting with jointless bridges constructed with integral abutments. Later, in the 1980s, researchers at Iowa State University developed a methodology for analysis of the piles in integral abutments. The methodology determines the depth at which a pile can be considered to have a fixed support. With an established location of fixity, the pile can be checked for ductility to ensure that it can flex without damage and can be checked as a column to ensure that it can support the abutment, end span, and traffic. With the methodology, it is possible to set general policy limits on the use of integral abutments, address industry trends, and consider unusual site conditions. Based on a parameter study, Iowa recently increased the bridge length limits for integral abutments to 575 feet for concrete superstructures and to 400 feet for steel superstructures, with reductions for skew. Use of compact, Grade 50 H-piles, or deeper prebored holes permits longer end spans to 150 feet or more for steel superstructures. On a case-by-case basis, the methodology permits consideration of piles with downdrag, retaining walls near abutments, unsymmetrical site conditions, and sites with bedrock near the surface. Use of jointless bridges reduces initial costs by eliminating bearings and expansion joints and reduces maintenance costs because there can be no damage from leaking joints. Expanding the use of jointless bridges with integral abutments has improved the overall life-cycle cost of Iowa bridges.

Title: Accelerating construction of bridge abutments: Legacy parkway project, UT
Author(s): K.N. Gunalan, Curt Christensen, Corbett Hansen, Ken Hirschmugi
Date: 2004
Doc ID/URL: *Geotechnical Special Publication n 126 I, Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans 2004*, 2004: 488-495.
Description: 8 pp.

Contents: Legacy Parkway is a proposed fully controlled access highway in Salt Lake/Davis Counties, Utah. The current Parkway alignment is located in the Lake Bonneville Basin. The near surface soils are composed of stream alluvium, lateral spread deposits, lacustrine silts and clays and marsh deposits. The geotechnical challenge along the proposed alignment includes settlements (both primary and secondary) in the range of few millimeters to upwards of 1000 millimeters over a period of time ranging from about 30 days to 2,000 days. The traditional approach of building the bridge embankments and allowing for the settlement to be complete before building the abutments would not allow the builder to meet the schedule constraints. A creative engineering approach, based on field data, helped accelerate the construction of bridge abutments before the settlements due to embankment loads were completed. This paper will present details of downdrag/dragloads on the bridge foundations due to settlements, analysis conducted, and the planned approach taken by the Design-Build Team to accelerate construction.

Title: Unified design of piled foundations with emphasis on settlement analysis (In *Current Practices and Future Trends in Deep Foundations*)
Author(s): B. H. Fellenius
Date: 2004
Doc ID/URL: *ASCE Geotechnical Special Publication 125*, 2004: 253-275.
Description: 23 pp.
Contents: Design of a piled foundation rarely includes a settlement analysis and is usually limited to determining that the factor of safety on pile capacity is equal to an at least value. This approach is uneconomical and, sometimes, unsafe. Every design of a piled foundation should establish the resistance distribution along the pile, determine the location of the force equilibrium (the neutral plane), estimate the magnitude of dragload from accumulated negative skin friction at the neutral plane, evaluate the length of the zone where the shear forces change from negative to positive direction, establish the load-movement relation for the pile toe and the load distribution in the pile at the time that settlement becomes an issue for the design, and finally, perform a settlement analysis. The settlement analysis of a piled foundation must distinguish between settlement due to causes other than the load on the piles. A fundamental realization of the design approach is that pile toe capacity is a misconception. Each of the mentioned points is addressed in this paper, and a design approach for the design of piled foundations and piled rafts is presented. Examples and case histories are included showing the distribution of measured and calculated resistance distribution along the piles and settlement of soil and piles.